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Research Article

Relationship between lake area and distance from the city centre on lake-dependent resident and migratory birds in urban Bangalore, a tropical mega-city in Southern India

Ravi Jambhekar [1,*], Kulbhushansingh Suryawanshi,[2,3] and Harini Nagendra[1]

[1]Centre for Climate Change and Sustainability, Azim Premji University, Burugunte Village, Survey No 66, Bikkanahalli Main Road, Sarjapura, Bengaluru, Karnataka 562125, India, [2]Nature Conservation Foundation, 1311, 'Amritha', 12th Main, Vijayanagar 1st Stage, Mysore 570017, India and [3]Snow Leopard Trust, 4649 Sunnyside Avenue North Suit, 325 Seattle, WA 98103, USA

*Corresponding author. E-mail: ravijambhekar04@gmail.com

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Abstract

Urbanization is one of the major causes of biodiversity loss worldwide. Some species are able to adapt to urbanization, whereas others perish. Studies on long-term effects of the impact of urbanization on species diversity and abundance patterns are especially lacking from tropical cities. We seek to assess the relationship between urbanization and species richness of lake-dependent birds in Bangalore, a tropical mega-city in Southern India. We specifically ask: (i) How is bird species richness related to the size of the lake? (ii) How is bird species richness in Bangalore's lakes related to the degree of urbanization? We used data from 2014 to 2019, collected from eBird—an online database that collates information on bird observations globally. Both lake area and distance from the city centre are correlated to species richness, with larger lakes supporting more bird species. As distance from the city centre increased (i.e. urbanization decreases), bird richness increased. Overall, in the city of Bangalore, migratory birds have declined while many lake-dependent resident birds seem to be increasing over the past 5 years. We hypothesize that birds that roost and nest in trees appear to be increasing. To confirm this, further research taking a trait-based approach is required. Urbanization appears to have species-specific impacts on lake-dependent birds in this tropical city, with certain groups of birds faring better than others. This research adds to the significant paucity of studies of the impact of urbanization on biodiversity in the urban tropics.

Key words: birds, tropical urban ecology, diversity, eBird

Introduction

Urbanization causes fragmentation, leading to a patchy landscape, habitat degradation and disturbance. Bird species distribution in a patchy environment can then be affected by the traits of the species and the habitat characteristics such as area and intensity of disturbance. Species-specific traits might be useful in understanding why some species thrive and others decline after fragmentation (Patankar et al. 2021).

Though there are many studies that assess the effects of fragmentation on species diversity patterns and patterns in abundance (Hansen et al. 2005; Faeth, Bang, and Sari 2011), information for most of the taxa in urban areas is still lacking. Information from tropical cities on the factors that influence the distribution of taxa such as birds is also largely lacking (Patankar et al. 2021). Some evidence suggests that level of urbanization and area of the patch have negative effects on forest bird species richness in cities (Suarez-Rubio and Thomlinson 2009). Other studies report that some species decline post-construction in urban areas indicating negative impacts of urbanization (Hostetler, Duncan, and Paul 2005) In Shanghai, China, research has shown that area and connectivity of certain habitats in the city can have serious negative impacts on bird communities (Xu et al. 2018), thus indicating the negative impacts of urbanization in most cases. In the city of Bangkok, yet another tropical city, large parks in the city support the greatest number of species, and other parks surrounding the large parks also had higher species diversity than small parks (Chaiyarat et al. 2019). A study from Taipei also finds that large green spaces support a greater diversity of birds as compared with smaller patches (Shih 2017). Many studies from the tropics report on bird species richness in urban green spaces, but relatively limited information is available on population level patterns of birds in tropical cities.

To answer some of these questions, data from long-term monitoring programmes, collected over multiple sites and across a gradient of landscapes is required. Citizen science initiatives which use standard protocols and are popular amongst bird watchers and nature enthusiasts would be ideal for asking such questions and can provide valuable insights (Wood et al. 2011; Callaghan and Gawlik 2015). We used data from eBird—one of the most popular citizen science projects globally—to ask questions about the relationship between urbanization and bird species richness of lake-dependent birds. eBird data might not be ideal in all areas, and temporal coverage of such data are likely to be less systematic than those of specifically designed bird monitoring surveys and may result in less accurate population estimates (Horns, Adler, and Şekercioğlu 2018). Opportunistic studies using citizen science data sources have reported results similar to formally conducted studies (Walker and Taylor 2017; Horns, Adler, and Şekercioğlu 2018). However, others have expressed concerns particularly when estimating population trends for common species (Kamp et al. 2016). Hence, care should be taken while framing questions that will make use of such data to answer questions.

We focussed on the relationship between urbanization and bird species richness in Bangalore—a fast growing tropical mega-city in Southern India. We focussed on lake-dependent bird species in urban areas as information on impacts of urbanization on lake-dependent birds in tropical urban areas is lacking. Wetlands are important for birds as they provide feeding, nesting and roosting sites for many birds (McKinney, Raposa, and Cournoyer 2011). Studies in the neotropics indicate that wetlands, whether natural or artificial, play a major role in maintaining local and regional diversity of birds (Murillo-Pacheco et al. 2018). Creation of wetlands has been shown to increase biodiversity. It is also reported that several small wetlands had similar abundances as one large wetland, indicating the importance of maintaining and creating wetlands for bird populations within a city (Kačergytė et al. 2021). Studies have shown that in cities, distance to water is an important factor affecting bird diversity (De Camargo Barbosa et al. 2020) and human disturbance and increase in construction have negative effects on bird diversity (Chen et al. 2021). Studies indicate that urban lakes are important to water birds and different birds use different areas along these lakes and lake edges in cities (Traut and Hostetler 2004). Accordingly, we decided to focus on water-bodies in urban areas.

Our goal was 2-fold, to assess the relationship between lake attributes, such as lake size, connectivity between the lakes and distance of these lakes from city centre, all used as measures of urbanization, and bird community distribution around the lakes, and to assess relationship between the degree of urbanization and lake-dependent bird populations over time. Bangalore has a large network of water bodies (lakes or tanks) connected by streams along a topographic gradient, that are now getting cut-off and isolated as an effect of urbanization. We focussed on birds as representative of the biodiversity of these lakes because they are quick to respond to changes in their habitat. We used ideas from the theory of island biogeography to assess the relationship between species diversity and associates of fragmentation such as the size of the habitat, connectivity between habitat patches and the degree of urbanization.

We specifically ask: (i) How is bird species richness related to the size of the lake? We expect that larger lakes will have more species of birds (ii) How is the degree of urbanization related to bird species richness in Bangalore's lakes? We expect that as distance from city centre increases (i.e. urbanization decreases), bird species richness would increase. (iii) How is the connectivity between lakes related to species richness? We expect that lakes that are more connected will have more diversity. We focussed on the entire bird community for Objectives (i–iii). However, we only focussed on lake-dependent birds for the fourth objective. (iv) How have lake-dependent bird populations fared over the years? We expect, that over time, as urbanization increases, number of bird species in the city would have decreased over the recent past (last 5 years). We further examine differences in the relationship between urbanization and species richness in different categories of birds, including of populations of resident and winter migrant bird species, and of different groups of water birds such as ducks, cormorants, waders and kingfishers, to understand how relationships with lake size and urbanization might play out differentially across different groups of birds. We focussed on ducks, cormorants, waders and kingfishers specifically as these groups comprised most of the common water birds observed in our dataset. These groups also had migratory and resident species to allow us to compare between resident and migratory species.

Methods

Study area

We focussed on urban birds in the city of Bangalore, Karnataka, India. Bangalore is one of India's fastest growing cities, with an area of 709 km^2 and a population of close to 20 million (Deb, Dhindaw, and King 2020). The suburban sprawl is much wider than 709 km^2 as the city is fast expanding. Bangalore was historically known as a city of lakes. The water bodies across the city have seen a lot of encroachment and reclamation over the past several decades (Nagendra 2016). According to government reports Bangalore has 189 lakes distributed within municipal boundaries.

In the city of Bangalore, a number of local government authorities and neighbourhood community groups have been involved with rejuvenation of lakes. The authorities are involved in activities such as deepening and desilting of lakes, cleaning polluted lakes through Sewage Treatment Plants, creating islands in the lake and controlling lake pollution (Karnataka Lake Conservation and Development Authority). These activities are described by local authorities as having resulted in a positive impact on lake birds by providing increased ecological habitat, and treating water pollution. Therefore, we decided to focus on waterbodies, bird species richness (all birds) and a set of birds, mostly dependent on these waterbodies to examine changes in bird populations over the years. A map of the lakes surveyed and the distribution of study sites is attached in the Supplementary Figs S1 and S2.

eBird data

eBird is an online database that collates information on bird observations by birdwatchers across the world (Sullivan et al. 2009; Wood et al. 2011). eBird data are widely used in scientific publications (Wood et al. 2011; Callaghan and Gawlik 2015; Walker and Taylor 2017; Ruiz-Gutierrez et al. 2021). These observations are reviewed by moderators using a filtering system (Sullivan et al. 2009). eBird data can be freely downloaded for any geographical region of the world. As of November 2020, over 21 500 observers have recorded over 1.1 million lists from India, of which 2469 observers had reported over 66 200 lists from Bangalore.

The basic unit of this data is a checklist of species. A checklist can be uploaded using one of the four protocols: (i) Travelling (ii) Stationary, (iii) Incidental and (iv) Historical. The 'incidental' protocol is used to upload a list when birdwatching is not the primary objective of the observer. The 'traveling' and 'stationary' protocols require the observer to include data on effort (start time, duration for stationary and start time, duration, distance for traveling). 'Historical' protocol is used when information on effort is not available. All lists include a location and observers are required to indicate whether a list is complete, i.e. all species seen are reported. We used lists with all the above protocols for our analysis.

We downloaded the eBird basic dataset for the state of Karnataka, as we wanted to focus on bird diversity in Bangalore city and also the periphery of the city. We marked a radius of 35 km from the city centre on Google Earth and filtered the eBird dataset to select the lakes that fall within this radius. The data were downloaded as a csv file which was used for all further analysis.

We selected all observations between January 2014 and March 2019. eBird checklists were included according to the following criteria: (i) only complete checklists were included (all birds seen and/or heard); (ii) Duplicate lists were filtered using group id column in the dataset and only unique lists were used for the analysis; (iii) Only hotspot data for each lake were used, so if a checklist for a lake was not added to the hotspot then it was excluded from the analysis. Hostspots have multiple observations, these locations are open to public and have well-defined boundaries and are moderated by eBird scientists. This might not be the case with other locations and hence we used only hotspot data; (iv) We included lists that used 'Incidental', 'Stationary', 'Traveling' and 'Historical' protocols; (v) We further filtered the checklists based on the list duration, we considered all lists of 10–100 min. We selected lists with a minimum duration of 10 min of observation. Based on our own extensive knowledge of this location, observations made in a period shorter than 10 min can fail to capture many species, thus under-representing the diversity of species. We plotted a histogram of the number of lists and time duration. We had a total of 6814 lists, 455 of all lists were <10 min of duration and 2720 lists were over 100 min. We were concerned that longer duration might not add more information to species richness and might have repeated observations of the same individuals; hence, we chose 100 min as our upper limit. Kelling et al. (2015) suggest that a higher time duration of checklists was useful in reporting more species. We were interested in reporting the change in species richness over the years; hence, we kept the higher cap of 100 min to capture the maximum diversity.

Bird species richness across years and lakes

We used smoothened rarefaction curve for standardized sample size to estimate total species richness across years 2014–2019 (Sullivan et al. 2009;). Sample size from 2014 was used as the standardized sample because it was the first year in the dataset and had the fewest number of samples. We used the package *Vegan* in R version 2.5-7 for this analysis (Oksanen et al. 2007). We also plotted the rarefaction curves using sampling duration to assess the rate of new species seen for each year.

We used total bird species reported at each lake to assess the relationship between urbanization and lake species richness. All lakes with fewer than 15 checklists over the years were dropped from the dataset as they are likely to under represent the diversity which these lakes might support due to inadequate sampling. Also, this sample size was insufficient for estimating species richness for each site using rarefaction analysis (Gotelli and Colwell 2001).

Environmental variables

For the lakes of interest, lake area was estimated using Google Earth. As a measure of urban gradient, we used the distance of the lake from the city centre as a proxy for intensity of urbanization (Dallimer et al. 2012). Ulsoor lake which is very close to the geographical centre of the city was considered the zero point. Nearest straight line distance of other lakes was estimated using the scale tool feature on Google Earth. Area of the habitat is known to play an important role on the species richness hence we also used lake area as another predictor variable. We also used the distance to the nearest neighbouring lake as a measure of connectivity between the lakes to analyse the difference between species richness.

Moran's I test was conducted on bird species richness and distance from city centre to test if there was a spatial autocorrelation between the lakes and bird species richness.

For each lake, bird species richness (includes all bird species) was estimated using species rarefaction curves using the plyr, tidyverse and vegan package in R (Oksanen et al. 2007; Wickham and Wickham 2017, 2020). Each checklist was treated as an independent survey and was considered as a datapoint for the analysis. We used total species richness obtained from rarefaction curves as a response variable, the area of the lake, distance to the nearest lake and distance from the city centre as the predictor variables and an interaction between area and distance from city centre in a linear model. The interaction term was not significant and so was dropped out of the model, retaining only the main predictors.

Changes in frequency of reporting of bird species over time

For this particular question, we were interested in bird species that are either water birds or are lake-dependent species, as these birds are likely to be the most affected by changes to lake area and reduced connectivity between lakes in the city. We focussed on lake-dependent birds to estimate changes in frequency of reporting, as a proxy for bird abundance of lake-dependent bird species over time. Based on natural history information and personal communications with two bird experts, Suhel Quader and Ashwin Vishwanathan (pers. comm.), ornithologists based in Bangalore with experience on eBird data from India, we selected only a set of bird species that are directly dependent on lakes, excluding birds that are widely distributed in habitats outside lakes. Some waterfowl species can be difficult to identify and there is a chance of being misidentified given their cryptic colouration, but given the strict review process which eBird follows, we expect if any such errors were there in the dataset, they are likely to be minimal and beyond our control. A total of 52 lakes and 92 bird species were selected for changes to bird diversity over time analysis (complete list in Supplementary Material, Lake names Supplementary Table S1 and Bird species in Supplementary Table S2). We had to further filter the lake and bird list due to insufficient observations over the years and the final sample size was 42 lakes and 72 bird species.

To estimate how the abundance of bird species has changed over the years, we calculated the frequency of reporting for each species for each year from 2014 to 2019. For each species, we summed the number of lists in which a species was seen in that year and divided it by the total number of lists reported during that year to calculate the change in frequency of reporting. Frequency of reporting was used in place of actual abundance as it is difficult to estimate the abundance given the variation in time of the lists and number of participants involved in the data collection process. A potential problem of double counts also, does not arise in our study, as we used presence absence data and not the actual abundance data for the change in frequency of reporting analysis. Change in frequency of reporting was used as a proxy for change in the populations of species over time [State of India's Birds (SoIB) 2020]. Frequency of reporting is a good measure of trends over time as it is not affected by the change in effort (total number of checklists) over time.

We used linear regression models with the species' annual frequency of reporting as the response variable and year as the explanatory variable to estimate the change in frequency of reporting as a proxy for abundance over the 6 years. A positive slope indicated an increase in frequency of reporting, i.e. an increase in the abundance of that bird species over time, whereas a negative slope indicated a decrease in frequency of reporting, i.e. a decline in that specific bird species over time. Bird species that were seen in <2 years in the period of 6 years were excluded from the changes to the frequency of reporting of bird species over time analysis, as there weren't enough sightings to fit a regression model to their frequency of reporting. This could also mean that the bird was a vagrant passing through the area. Analysis was done in R programming language (R Core Team 2019). Finally, after application of this criterion we were left with a sample size of 44 lakes and 72 bird species.

We also studied a few groups of common and widely occurring bird species more closely to see if some groups have benefitted from or suffered losses due to urbanization and lake rejuvenation. We present the results for migratory and resident species separately to assess potential difference between them. However, migratory species at our study sites are very variable with some species occurring almost year around (e.g. Green Sandpiper and other species occurring only for 3 months). We did not analysis for the duration of the stay for the migratory species.

RESULTS

We had a sample size of 3487 lists that fitted our criteria. Over the years, number of lists that are being uploaded have also increased; 2014 had 220 lists that fitted our criterion but 2019 had 780 lists that fitted our criterion. We used data from 44 lakes in and around the city of Bangalore. A total of 263 species were observed from 2014 to 2019 in these 44 lakes. The cumulative species richness for the years are 170 species in 2014, 184 species in 2015, 217 species in 2016, 199 species in 2017, 218 species in 2018 and 204 species in 2019. Figure 1a shows the variation in species richness from 2014 to 2019. To compare across years, we used estimates of species richness for each year from smoothened rarefaction analysis for a standardized sample of 54 537 individuals. Estimated species richness ranged from 178 to 218 species (Fig. 1b) but there was no clear trend over the years. Year 2016 had the highest species richness as compared with other years (estimate = 193, SE = 3.4), followed by 2018 (estimate = 192, SE = 3.40). We used 2014 as the starting year, and the species richness was the lowest for that year (estimate = 170, SE = 0). Estimated species richness for 2015 was estimate = 178, SE = 2.0; 2017 was estimate = 186, SE = 2.70; 2019 was estimate = 183, SE = 3.20.

The result of the Moran's I test on bird species richness and distance from city centre was significant, indicating spatial autocorrelation between the lakes and bird species richness ($P = 0.001$).

Impact of urbanization on lake bird diversity

Lake area exhibited a positive relationship with total species richness. As the area of lake increased the species richness also increased (Estimate = 36.96, SE = 14.45, $P = 0.07$, $R^2 = 0.42$; Fig. 2a). Similarly, as distance from city centre increased the estimated bird species richness also increased. That is, the lakes in the city centre had fewer number of species but as we moved towards the outskirts of the city the bird species richness increased (Estimate = 2.14, SE = 0.89, $P = 0.02$, $R^2 = 0.42$; Fig. 2b). Distance to the nearest lake did not have any significant relationship to bird species richness (Estimate = 0.43, SE = 3.22, $P = 0.89$, $R^2 = 0.42$) We also find that the larger lakes were located away from the city centre (Estimate = 0.04, SE = 0.01, $P = 0.0005$, $R^2 = 0.32$).

Changes in frequency of reporting of bird species over time

We analysed data for change in the frequency of reporting for 67 species over 5 years. Fifty-two species did not show any discernible statistical trend. Nine species showed a significant increasing trend and six species showed a significant decreasing trend ($P < 0.05$).

We examined which types of birds were increasing or decreasing, further dividing them into two main categories, i.e. migrants and residents. We were unable to find any trends by habitat or feeding behaviour—e.g. shore-dependent birds or fish-eating birds did not show any particular pattern in their trend in frequency of reporting over the years (Fig. 3a). However, migrant species consistently declined across all groups while resident species increased (Fig. 3b).

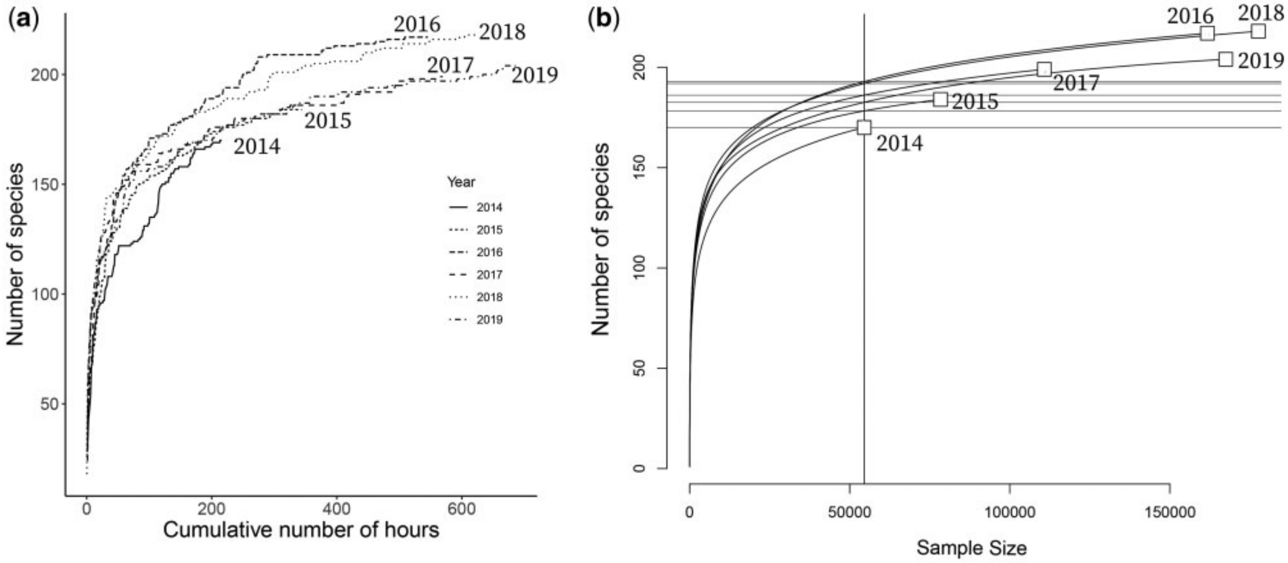

Figure 1. (**a**) Variation in bird species richness from 2014 to 2019. We considered data from 2014 for all further analysis. A total of 263 species were observed in 44 lakes across the city of Bangalore. (**b**) Rarefaction of bird species richness across the years. Vertical line indicates the minimum number of individuals used to estimate species richness across all the 6 years. The horizontal lines indicate the species richness at the comparable sample size of 54 537 individuals.

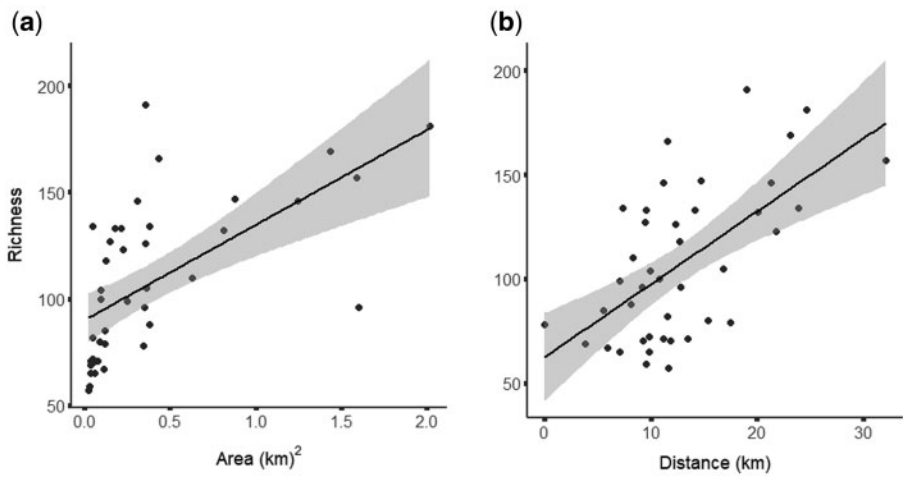

Figure 2. Relationship between bird species richness. (**a**) Area of the lake and (**b**) distance from city centre. The black line represents the slope and the shaded area is 95% CIs for 44 lakes in Bangalore.

For species belonging to order Suliformes, like Indian cormorant (*Phalacrocorax fuscicollis*; slope = 0.03, $P < 0.04$), little cormorant (*Microcarbo niger*; slope = 0.02, $P < 0.04$) and oriental darter (*Anhinga melanogaster*; slope = 0.01, $P < 0.04$) all showed a statistically increasing trend. Similarly, for stork species (order: Ciconiiformes), painted stork (*Mycteria leucocephala*; slope = 0.03, $P < 0.001$), showed an increasing trend. Other species that showed a statistically increasing trend were black-crowned night heron (*Nycticorax nycticorax*; slope = 0.009, $P < 0.01$), Brahminy kite (*Haliastur indus*; slope = 0.012, $P < 0.006$), little egret (*Egretta garzetta*; slope = 0.023, $P < 0.012$), red avadavat (*Amandava amandava*; slope = 0.005, $P < 0.045$). Although other groups of birds such as ducks, order: cotton pygmy goose (*Nettapus coromandelianus*; slope = −0.002, $P < 0.04$), northern pintail (*Anas acuta*; slope = −0.003, $P < 0.04$), showed significant declines. Purple heron (*Ardea purpurea*; slope = −0.026, $P < 0.043$) and pheasant-tailed jacana (*Hydrophasianus chirurgus*; slope = −0.015, $P < 0.05$), green sandpiper (*Tringa ochropus*; slope = −0.017, $P < 0.43$), wood sandpiper (*Tringa glareola*; slope = −0.016, $P < 0.035$) were the other species that showed significant declining trends across the years.

Discussion

Both lake area and distance from the city centre are related to species richness of lake-dependent bird community in Bangalore. However, connectivity between the lakes did not have a significant relationship to the species richness of lake-dependent bird community. Larger lakes had more bird species as compared with smaller lakes. Lakes that are in the centre of the city had fewer species as compared with lakes that were away from the city centre. Overall, in the city of Bangalore migratory birds are declining while many lake-dependent resident birds seem to be increasing over the past 5 years. There was no consistent decline or increase in the species richness reported over the years.

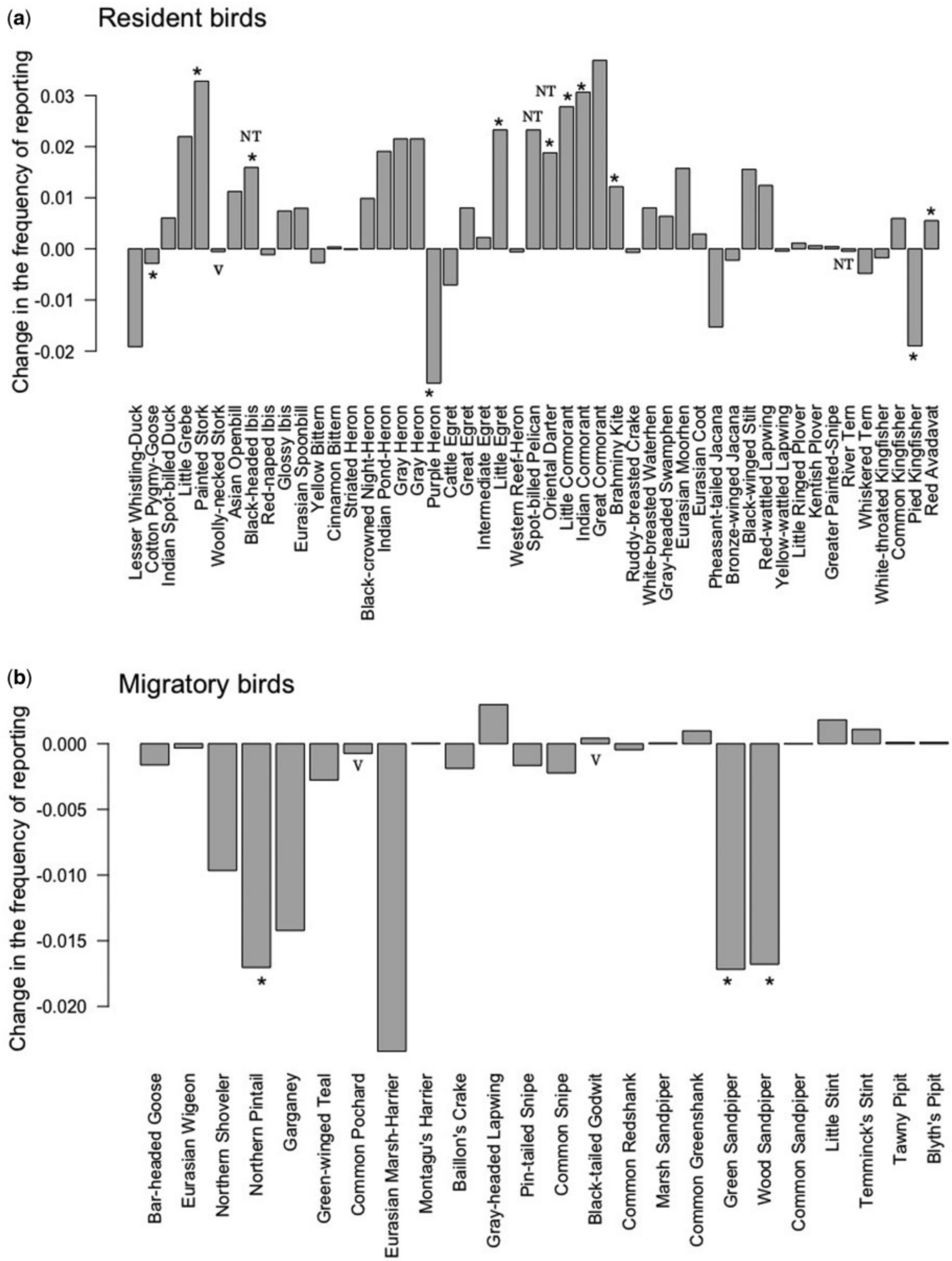

Figure 3. Trends in frequency of reporting from 2014 to 2019. (**a**) Resident birds. (**b**) Migratory birds. Y-axis represents the slope (coefficient) of the regression between the frequency of reporting and year, a measure of trend in the reporting of each species over the span of 2014–2019 years. X- axis has species identity. Asterisk (*) indicates species for which the change was statistically significant ($P < 0.05$). V, vulnerable species; NT, near threatened species according to IUCN (International Union for Conservation of Nature) status.

Many previous studies have highlighted the effects of urbanization on general bird diversity (Silva, Sepúlveda, and Barbosa 2016). We had hypothesized that lakes that are in the centre of the city will have less diversity as these lakes are most likely to be disturbed, might have polluted waters and might not have the right habitat conditions required by the lake birds because of human presence (Phillips et al. 2018). We find that indeed the lakes in the city centre have fewer number of species.

We also observed a relationship between habitat area and decline in species richness. Larger lakes supported more diversity as compared with smaller lakes. Larger areas are likely to have more resting and breeding spaces, feeding resources and microhabitats required for birds and hence they supported more number of species (Callaghan et al. 2018). Although a recent study from Delhi, another mega-city from the tropics, found that even small ponds support high bird diversity in cities (Rawal et al. 2021).

However, we find that the connectivity between lakes was not significantly related to bird species richness in the city. There could be two possible reasons for this, one being the lakes are well connected despite the urbanization and birds are able to fly between the habitat patches (lakes) or the second reason being birds are able to move large distances and hence are not affected by the distance between these lakes. Species-specific studies focussing on bird movement might be required to answer this question in detail.

We found that area of the lake was positively correlated with the distance from city centre thus we cannot conclude which of the two is has greater importance in determining species richness. However, urbanization is the primary associate of the decline in lake size closer to the city centre (Nagendra 2010, 2016). Therefore, we hypothesize that direct effects of urbanization and indirect effects through changes in lake size may be influencing bird species richness.

When we compared resident and winter migrant species, we find that winter migrant birds showed a steep decline over time (Wilcove and Wikelski 2008; Gilroy et al. 2016). These declines in migrant species are likely to be associated with conditions on the breeding grounds rather than on the wintering grounds, as similar findings were also reported in SoIB (2020) report. However, it is also likely that migratory species have moved their wintering grounds away from urban centres like Bangalore in their wintering grounds in the tropics. These two ideas need to be examined in greater detail in the future. Winter migrants arriving in Bangalore vary greatly in their breeding grounds (ranging from the Himalaya to the Tundra) and duration they spend in Bangalore. Our results are only indicative that the decline in wintering species needs further research attention. Since we excluded rare species which were seen less than two times in the span of 6 years, we might have excluded vagrants and therefore we cannot comment on changes in migratory status of vagrant birds visiting the city. The resident birds showed an increasing trend in change in frequency of reporting. We speculate that recent lake restoration that has been widespread across Bangalore has helped resident lake-dependent birds to thrive.

We also find that birds that nest in tree canopy such as cormorants, painted stork, Brahminy kite and egrets are increasing. This might be because of availability of nesting sites in the islands created by the authorities that have tall trees. Many of these species are also piscivores and another reason for their increase could be the increase of fish in the lakes, the main prey of these birds (Boyle, Dorn, and Cook 2014). Surprisingly, despite major changes to the banks of the lakes there was not much decline in the shorebirds except for the migrants which are declining across the country (SoIB 2020).

We found that certain species such as purple heron (*A. purpurea*) and cotton pygmy goose (*N. coromandelianus*) are locally common and non-migratory but were still declining. One reason, we hypothesize, is that cotton pygmy goose is a cavity nesting species. Due to lack of suitable nesting sites this species might be declining (Upadhyaya and Saikia 2010). The other reason behind decline of some of the resident species might be competition from other dominant resident species. Similar effects have been observed in other studies (Wittwer et al. 2015). These effects may have to be examined in detail in future research.

When we examine groups of species, we find that in certain groups, most species show a negative slope in frequency of reporting. For example, 9 of the 10 duck species in our analysis had a negative slope, being detected in fewer number of checklists over the years, indicating lesser abundances, although the *P*-value was significant only for two species. Most duck species are ground nesting and migratory, two traits known to be associated with increased species vulnerability (Haskell, Knupp, and Schneider 2001). We hypothesize that the decline in duck populations might be associated with urban pressure on their breeding grounds (perhaps from feral dogs and cats, or other unknown forms of pressure) and these declines are being reflected in the migratory sites too. This general pattern has been reported in recent studies, wherein ducks and other waterfowl are declining in Asian countries due to lack of governance when waterbodies and wetlands were concerned (Amano et al. 2018).

The three species of cormorants and one species of darters had positive slopes and for three of these four species the slope was statistically significant. All these species are resident to the Indian sub-continent. These birds nest in the tree canopies and maybe they are benefitting from the creation of islands in the lakes. Also, rejuvenation of lakes in terms of desilting, creation of islands and introduction of fish stocks to these lakes, might be leading to increase in food availability in the lakes helping these birds to maintain stable populations in cities. All lakes have not experienced similar restoration efforts. We suggest a future study on lakes in which islands were created recently and lakes which do not have islands, comparing them to assess changes in bird diversity and populations. A before and after study of lakes that have undergone rejuvenation can also be insightful.

Contrary to general expectation, we find that most (32 out of 49) lake-dependent species in our dataset that are resident year around showed an increasing trend (Fig. 2a); for eight of the resident birds the increase was statistically significant. Only three resident species showed a statistically significant decline. Most of the species showing significant increasing trends seem to have benefitted from the creation of islands with trees which they might be using for nesting and roosting. Nearly half of these species are obligate piscivores, perhaps benefitting from the management of lakes for commercial fish production (Dombeck, Hammill, and Bullen 1984; Kirby, Holmes, and Sellers 1996). We have identified the species that show a declining trend. The use of frequency of reporting as a proxy for bird abundance is debatable, however, they are widely used to identify trends in changes over time (Szabo et al. 2010). We have discussed the results of this analysis in relation to the country wide analysis using similar methods (SoIB 2020). We have been cautious of interpreting them in isolation. These results are the first step in identifying the questions and hypotheses that need to be tested in tropical urban systems. Focussed research on these species and examination of their traits could help identify the causes of their declines and help habitat management to arrest their declines. Creation of cavity nesting habitats on the island is one such management activity which can be undertaken.

Our results support the hypothesis that urbanization affects species diversity and certain species might be more vulnerable to the pressures of urbanization as compared with others. Some species that have special adaptions such as adaptability to use multiple nesting sites or wide diet choice can exploit the urban areas (Patankar et al. 2021). More detailed analysis and species-specific studies looking at nesting and breeding behaviour and feeding habits can help predict and explain the mechanisms behind these patterns in changes in populations in urban birds.

Since we used eBird data, factors such as number of observers and effort in terms of time varied widely and were beyond our control (Kelling et al. 2015). On field observations with a standardized study protocol can add to more robust findings, controlling spatial sampling bias. For example, if certain areas or demographics of the city have fewer birdwatchers contributing eBird checklists, these can be added to get more uniform coverage of bird checklists from all parts of the city. There are certain limitations of using eBird data, such as temporal coverage of such data are less systematic than those of specifically designed bird monitoring surveys; it is difficult to use eBird data to make direct abundance estimates; over-emphasis of citizen birders on rare species (Horns, Adler, and Şekercioğlu 2018). There is also the risk of misidentification of cryptic and lesser-known species. However, eBird is also an invaluable resource of data for studying data poor systems, especially in the tropics, where there is a paucity of such studies. We have used eBird data to study common lake birds from hotspots and hence the limitations of eBird are less likely to affect our conclusions, but nonetheless, we advise caution in drawing strong causal relationships from these patterns. Future studies could consider combining primary data with data collected by citizen scientists to strengthen our understanding of urban ecology in the tropics. Along with eBird data from more cities and species, analysis of functional traits can be used to increase our understanding of ecological processes and predict species vulnerability in urban areas. Supervised governance, raising awareness about bird diversity in wetlands along with systematic investigation of possible causes of declines can help in effective recovery of birds in cities (Amano et al. 2018).

Supplementary data

Supplementary data are available at *JUECOL* online.

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